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Fate and Effects of Whole Drilling Fluids and Fluid Components in Terrestrial and Freshwater Ecosystems: A Literature Review

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FATE AND EFFECTS OF WHOLE DRILLING FLUIDS AND FLUID COMPONENTS IN TERRESTRIAL AND FRESHWATER ECOSYSTEMS: A LITERATURE REVIEW

to

U.S. ENVIRONMENTAL PROTECTION AGENCY

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Drilling fluids represent an important aspect of offshore and land based drilling operations. The fluids perform a multiplicity of functions, ranging from lubricating to prevention of blowouts when encountering high pressure. Periodically, the fluids must be changed or they become old and the spent fluids are disposed of in on-land facilities. Introduction into the environment of the chemically complex fluids has prompted e-fects research addressing terrestrial and freshwater habitats and their respective biological components.

Studies with terrestrial plants in laboratory and field experiments show that the fluids and some fluid components exhibit phytoxicity properties reducing seed germination, growth and yield. Phytotoxicity in whole drilling fluids is attributed to soluble salt concentrations.

Perference/avoidance reactions were observed in experiments with whole drilling fluids are also collated and discussed. The range of lethal concentrations of fluid components in toxicity studies was from < 1 to 75,000 mg/l and that for whole drilling fluids from 0.29 to 85% by volume. Various reasons for observed toxicity are discussed and recommendations made for future freshwater and terrestrial research with drilling fluids.

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ABSTRACT

Drilling fluids represent an important aspect of offshore and land based drilling operations. The fluids perform a multiplicity of functions, ranging from lubricating to prevention of blowouts when encountering high pressure. Periodically, the fluids must be changed or they become old and the spent fluids are disposed of in on-land facilities. Introduction into the environment of the chemically complex fluids has prompted effects research addressing terrestrial and freshwater habitats and their respective biological components.

Studies with terrestrial plants in laboratory and field experiments show that the fluids and some fluid components exhibit phytotoxicity properties reducing seed germination, growth and yield. Phytotoxicity in whole drilling fluids is attributed to soluble salt concentrations.

Preference/avoidance reactions were observed in experiments with whole drilling fluids using fish. The toxic properties of fluids components and whole drilling fluids are also collated and discussed. The range of lethal concentrations of fluid components in toxicity studies was from < 1 to 75,000 mg/l and that for whole drilling fluids from 0.29 to 85 % by volume. Various reasons for observed toxicity are discussed and recommendations made for future freshwater and terrestrial research with drilling fluids.

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INTRODUCTION

The most modern drilling method is the rotary system which requires a circulation of drilling fluid through the well bore while drilling proceeds. The drilling fluids are pumped from the ground surface through a drill pipe and bit to the bottom of the hole and returned through the annulus between the hole and the drill pipe.

Drilling fluid - mud - is usually a mixture of water, clay, weighting material and variety of chemicals to adjust the properties of the fluid to meet requirements of each well. Drilling fluid is a major factor in the success of the drilling program. It is used in offshore and land based operations and functions:

1. To remove the cuttings from the bottom of the hole and carry them to the surface.
2. To transmit hydraulic horsepower to the drill bit.
3. To cool and lubricate the drill string and bit.
4. To exert sufficient hydrostatic pressure to control fluids and pressure encountered in formations.
5. To minimize settling of cuttings and weight material in suspension when circulation is temporarily stopped. The mud, however, should have properties which allow the cuttings to settle in the surface system.
6. To support and protect the walls of the hole.
7. To reduce to a minimum any harm to the formations penetrated.
8. To insure maximum information about the formations penetrated.

Because of the multiple demands on the fluid it is not surprising that over 600 brand name additives are on the market for use in preparing drilling muds (Shaw 75). These "additives" can be categorized into four main groups, i.e., cooling and lubricating the drills, flotation of rock cuttings, sealing porous layers of the geologic strata, and solving various other problems. Common cooling and lubricating components are the fluid base itself

(usually water), sodium saturated bentonite clays, and for high temperatures, diesel oil. Organic polymers, carboxymethyl cellulose and polyacrylates are also sometimes used.

For removing cuttings from the hole a denser (heavier) fluid than water is usually used. The material most widely used is barite (barium sulfate) which has a density of 4. Two other weighting materials that are less frequently used are calcite (calcium carbonate) and siderite (iron carbonate).

As drilling penetrates sandstones or shales drilling fluid may be lost in excessive amounts unless the porous area is sealed. Flocculation of clays and inclusion of fibers of some type is the usual approach to sealing formations. A variety of chemicals and mixtures are used for this purpose some of which are: calcium chloride, calcium sulfate, calcium oxide, calcium lignosulfonate, sodium chloride, sodium silicate, colloidal asphalt, sulfonated asphalt, polyanionic cellulose, gilsonite and aluminum lignosulfonate.

The fourth category "solving other problems" involves controlling four mechanical or physical properties: (1) density, (2) viscosity, (3) gel strength, and (4) filtration. The main specific problems addressed by these properties are:

1. Contamination
2. Abnormal Pressure
3. Corrosion
4. Formation
5. Mud Characteristics
6. Slow Drilling Rate
7. High Temperature
8. Bearing Failure

Each problem is handled by altering the physical nature of (dilution, raise weight, adjust flow properties, etc.) or chemical nature (adjust pH, add chemical additives) of the drilling fluid (IACD 1974).

An entire "science" has developed around drilling fluids and their use in the petroleum industry. This brief introduction is meant only to serve

as an indication of the physical and chemical complexities one must be aware of when addressing the fate and effects of drilling fluids (muds) in the environment.

FATE AND EXPOSURE

Disposal Practices

Drilling fluids become contaminated, old or must be replaced because of down-hole conditions, therefore, the fluids are disposed of periodically. On-land when drilling operations are completed the active mud system may be jetted into a reserve pit (pond constructed on-site) and the active pits filled. The reserve pit (which may hold up to 100,000 barrels per site) is allowed to evaporate until it is dry, the retaining walls leveled and the contents of the reserve pit are spread and graded, (Specken 1975, Allred 1980). Although practices vary with geographical location the disposal of drilling wastes is usually by one of the following methods:

1. Dewatering of the reserve pit contents and subsequent backfilling with pit walls (example described above).
2. Landfarming the reserve pit contents into the soils around the drilling location.
3. Removal by trucks to other sites.
4. Pump wastes back down the well annulus.
5. Chemically modify the waste into a dry, inert substance.

The most common practice for fluid disposal is included in the first two options. Unlike offshore marine drilling operations, disposal of offshore drilling fluids from freshwater operations is usually accomplished by transporting the fluids to shore where they are handled as described above.

Surface and Groundwater Contamination

The introduction of drilling fluids into the environment is limited to accidental releases and disposal in terrestrial sites. Although little

drilling is presently being done in freshwater lakes, drilling muds and cuttings generated during their operations are usually transported to shore and disposed of on land.

Drilling wastes can be considered pollutants primarily because they contain high concentrations of organic carbon, total nitrogen, phosphorous, solids, chemical oxygen demand, and metals (Bryant et. al. 1974). Shaw and Keeley (1975) discussed the potential for polluting subsurface water supplies through drilling and subsequent contamination and Shaw (1975) outlined sampling and testing methods for toxicity studies with drilling fluids.

The contamination of surface water can be considered from both surface activities and also from contamination of groundwater from the borehole (Campbell and Gray 1975). The contamination of groundwater is important since many surface water habitats have an ultimate hydraulic connection with groundwater aquifers.

Aquifiers can be contaminated from stream runoff, abandoned wells, percolation of spilled muds, discarded materials, and leaching of fluids from earthen pits. One of the worst and widespread problems in drilling is lost circulation and subsequent contamination of aquifers. Lost circulation results from openings in the formation large enough to accept whole mud. While drilling with water seepage may occur into porous, permeable formations exposed to the borehole. Finally, through a blowout uncontrolled entry of fluids into the borehole may force gas into shallow aquifers and cause water wells to be contaminated (Campbell and Gray 1975).

The contamination of soils, surface water and groundwater is a source of impact to both plants and animals. A discussion of adverse impacts of drilling fluid components and whole drilling fluids on plants and animals will be addressed in the following discussion.

Throughout the remainder of the discussion the terminology drilling fluids and drilling muds will be used interchangeably and will refer to the material used during drilling operations. Sump fluids, although composed primarily of drilling muds, may also contain rig wash, fuels, lubricating oils, etc. from rig operations. Studies performed with sump fluids will be so designated.

The toxicity and impact of drilling fluids can only be evaluated on the basis of its availability for reactions with biota. Because drilling muds and sump fluids, containing muds, are often incorporated into the soils adjacent to the well site (Allred 1980), consideration must be given to the bioavailability of potentially toxic components to plant species. Nelson et. al. (1980) addressed this question in laboratory studies with prepared drilling muds one containing barite low in toxic metals and the other having significant levels of Hg, Zn, Pb, Cd, Cu, and As. Their results suggest that the uptake of Cd, Zn, Cu, and Pb and concentration in the leafy portions of plants was directly related to the total amount of these metals in the rooting medium. Mercury found in the muds was not available to the plants. However, this study suggests that some metals (e.g., Cd, Zn, Cu and Pb) present in drilling muds are available for plant uptake and accumulation.

The exposure of aquatic biota to toxic chemical components of drilling muds released from offshore drilling operations in freshwater lakes has not been studied in detail. Ferrante et. al. (1980) studied the discharge plume from an offshore rig in Lake Erie. Although only small amounts of mud were discharged during drilling operations, plume dynamics were monitored and particulate discharges tracked. The plume configurations indicated that the fine clay sized particulate remained in the uppermost portion of the water column (0-4 m) and had a tendency to "river"; that is, remain together in a defined plume strung out in a down-current direction from the rig. Additional data from modeling efforts during the study suggested that larger particulates discharged tended to settle out in increasing distances depending upon particle size. Chemical constituents of the discharged fluids were also followed in the plume survey. Dilution of most chemicals was rapid with ambient concentrations being reached within 100 m of the discharge. Exposure to toxic materials may thus be limited to a relatively small area immediately around the rig. However, the behavior of some fish species to turbidity suggests that the discharge plume may act as an attractor (Lawrence and Scherer, 1974). This phenomena needs to be studied in detail before an exposure factor can be determined.

IMPACTS: INDIVIDUAL DRILLING FLUIDS COMPONENTS

Several approaches have been followed by investigators in determining the toxicity of drilling fluids to plant and animal species. Each approach depends on the form of the material which the experimental organism is exposed. The three distinct categories evident in literature are: exposure to individual drilling fluid components, exposure to a prepared (fresh) drilling fluid, and exposure to drilling fluids collected during drilling operations or immediately following (Tables 1 and 2).

Plants

A limited number of studies with drilling fluid components have been performed using terrestrial plants. Initial studies by Miller (1978) on drilling mud components indicated that a number of these components: asbestos, asphalt, a vinyl acetate, maleic anhydride co-polymers, bentonite clay, sodium polyacrylate, an ethoxylated nonyl phenol, a gilsonite paraformaldehyde, Dowmade, shell-supplied polymer, acid pyrophosphate, and sodium carboxymethyl cellulose caused slight reductions in yield or no effect at all when tested on beans and corn. Barite, modified tannin, filming amine, xanthum gum, lignite, modified asphalt and sulfonated tall oil had a more obvious effect reducing yield of experimental plant species.

Using high/excess addition rates of soil-mud , Miller observed significant reductions in yield when modified tannin, a non-fermenting starch, pregelatinized starch, iron chrome lignosulfonate, guar gum and a synthetic and natural plant fiber were tested. The most severe reductions were observed when sodium dichromate, diesel oil, potassium chloride or a mixture of calcium lignosulfonate and lignite were used.

Phytotoxicity studies reported in Miller and Honarvar (1975) and Miller et. al. (1980), showed similar results for 31 drilling mud components. Corn and beans were exposed to high and low rates of applications. The low rate was typical of field concentrations. Of the 31 components tested 10 caused a reduction in growth of both plant species, 1 caused increased plant growth of the beans. Four affected (other than growth) both beans and corn,

TABLE 1. SUMMARY: MAJOR STUDIES OF WHOLE DRILLING FLUIDS, WHOLE SUMP FLUIDS AND DRILLING FLUID COMPONENT EFFECTS ON PLANT AND ANIMAL SPECIES

Authors	Year	Test Organism	Test Fluid	Test Effect	Effect Notation	Test
			Plants			
Honarvar	1975	Beans and sweet corn	Drilling fluids components	Phytotoxicity	% yield	--
Miller and Honarvar	1975	Beans and sweet corn	Drilling fluids components	Phytotoxicity	Relative growth	--
Pesaran	1977	Beans and sweet corn	Drilling fluid mixture	Phytotoxicity	Seed germination/ relative growth	--
Miller and Pesaran	1980	Beans and sweet corn	Whole drilling fluids	Phytotoxicity	% yield	--
Miller et. al.	1980	Beans and sweet corn	Drilling fluids components	Phytotoxicity	Relative growth	--
Yonkin and Johnson	1980	Natural asemblage	Whole drilling and sump fluids	Seed germination and plant productivity	% seed germination and growth	in situ

TABLE 1 (Continued). SUMMARY: MAJOR STUDIES OF WHOLE DRILLING FLUIDS, WHOLE SUMP FLUIDS AND DRILLING FLUID COMPONENT EFFECTS ON PLANT AND ANIMAL SPECIES

Authors	Year	Test Organism	Test Fluid	Test Effect	Effect Notation	Test
			Animals			
Falk and Lawrence	1973	9-spine stickleback Lake Chubb	Whole sump fluids	Mortality	96 hour LC50 (% vol.)	Static/ in situ
Logan	1973	Rainbow trout	Whole drilling fluids and components	Mortality	96 hour LC50 (% vol. and mg/l)	Static
Lawrence and Scherer	1974	Whitefish and Rainbow trout	Whole drilling fluids and supernatant	Avoidance behavior	Preference/ avoidance	Flow-through
Beak Consultants	1974	Rainbow trout	Whole drilling fluids	Mortality	96 hour LC50 (% vol.)	Static
Didiuk and Wright	1975	Chironomid	Whole sump fluid	Larval survival	% emergence	Static
Weir and Moore	1975	Rainbow trout	Whole drilling fluids	Mortality	96 hour Lc50 (% vol.)	Static
Hollingsworth and Lockhart	1975	Sailfin Molly	Drilling fluids components	Mortality	MTL (ppm)	Static
Moore et. al.	1976	Rainbow trout	Whole drilling fluids	Mortality	96 hour LC50 (% vol.)	Static
Weir et. al.	1976	Rainbow trout	Whole sump fluids	Mortality	96 hour LC50 (% vol.)	Static
Hardin	1976	Phytoplankton amphipods 9-spine stickleback	Whole sump fluids	Mortality	96 hour LC50 (% vol.)	Static

TABLE 1 (Continued). SUMMARY: MAJOR STUDIES OF WHOLE DRILLING FLUIDS, WHOLE SUMP FLUIDS AND DRILLING FLUID COMPONENT EFFECTS ON PLANT AND ANIMAL SPECIES

Authors	Year	Test Organism	Test Fluid	Test Effect	Effect Notation	Test
Sprague and Logan	1976	Rainbow trout	Drilling fluids components	Mortality	96 hour LC50 (% vol. and mg/l)	Static
Beckett et. al.	1976	Rainbow trout	Drilling fluids components	Mortality	96 hour LC50 (mg/l)	Static
Lawrence	1980	Natural Assemblage	Whole sump fluids	Behavior/ mortality	Observations	In situ
Logan	1980	Rainbow trout	Whole drilling fluids	Mortaity	96 hour LC50 (% vol.)	Static

TABLE 2. TOXICITY OF DRILLING FLUID COMPONENTS TO RAINBOW TROUT (Salmo gairdneri)

Drilling Fluid Component	96 Hour LC50 (mg/L) Beckett et. al. (1976)	Logan et. al. (1973)	Sprague and Logan (1979)
Aluminum stearate	1100		
Barafloc	800		
Barite	Random; >10,000	>7500	76,000
Ben-Ex (polymer)	1300	665	660
Carbonox (lignetic material)	6500		
Cypan (sodium polyacrylates)	1200-1300		
Desco (organic thinner)	1200		
Dextrid (organic polymer)	<1		
DFE-506 normal	250		
neutralized	3500		
Diammonium phosphate	950		
Dowicide-B	0.75		
Drillaid 421	280-550		
Drispac (polyanionic cellulose)	2700-2800		
FLR-100	2200-4000		>1000
Hydrogel (Wyoming bentonite)	7200		
Kelzan XC polymer (xanthum gum biopolymer)	1800-2200	440	420[a]
Kwik-vis	1600		
Mil-Flo	600		
Muriate	2100		
Peltex • normal (ferrochrome lignosulfonate)	560-840		
• neutralized	>3200		
Protectomagic (asphalt)	5000-75,000		
Q Broxin (ferrochrome lignosulfonate)	1500-2000	1530	1500
Rapidril (organic polymer)	550		

TABLE 2. TOXICITY OF DRILLING FLUID COMPONENTS TO RAINBOW TROUT (*Salmo gairdneri*) (Continued)

Drilling Fluid Component	96 Hour LC50 (mg/L)		
	Beckett et. al. (1976)	Logan et. al. (1973)	Sprague and Logan (1979)
Salt mud (attapulgite clay)	23,500		
Sodium acid pyrophosphate	1700		840
Spersene (chrome lignosulfonate)	2500-5000		
Unical (chrome mod. sodium lignosulfonate)	860		
Visbestos (inorganic emulsion mud)	2750		
Walnut shells	2800		
Bentonite clay		>10,500	19,000
Carboxymethyl cellulose		>10,500	>10,000
Torq-Trim (sulphated triglycerides, alephetic and isopropyl alcohols			1300[a]
Sta flo			>1000
SS-100			>1000
Chromolit (potassium chromic sulphate)			750[a]
Metso beads			240[a]
Caustic (NaOH)		105	110
Tri-Cron (dihydroxy-propane and alkyl auryl sulphonates)			75[a]
Capryl alcohol			75[a]
Paraformaldehyde			60
Skot-Free			48
Potassium chloride		2020	
Sodium bicarbonate		7550	
Calcium chloride		>10,500	
B-Free			18

[a] Interpolated

but six others affected only one of the species. Examples of affects observed during testing are reduction in growth, decrease in germination, and dropping of leaves. The most toxic compounds tested, listed in order of severity of affect were: potassium chloride > lignite > calcium lignosulfonate > diesel oil.

Aquatic Animals

The purpose of a number of toxicity studies performed with aquatic animals was to acquire information on the toxicity of drilling fluids components in the aquatic environment (Falk and Lawrence 1973, Hollingsworth and Lockhart 1975, Beckett et. al. 1976, Sprague and Logan 1979, and Logan 1980). Emphasis in these studies was often placed on the toxicity to a sensitive freshwater fish species, usually rainbow trout (Salmo gairdneri). Several of the studies also addressed more specific questions such as: the effect of ageing on the toxicity of the most lethal chemicals (Sprague and Logan 1980), toxicity of specific compounds, e.g., thinning agents (Hollingsworth and Lockhart 1975), and predictability of toxic interactions of chemical components in standard drilling fluids (Sprague and Logan 1979).

Testing protocols varied with 96 hours static testing the "normal" approach although some investigators chose to adjust pH, stir or circulate continuously, and aerate throughout the test. Acute lethal toxicity tests by Logan et. al. (1973) (appendix to Falk and Lawrence 1973) indicated that almost half (13 of 27) of the mud components they tested were toxic with LC50's < 1000 ppm. Of the 13 compounds tested, 7 were very toxic and 6 were moderately toxic. Acute toxicities of 34 drilling fluid components (Table 2) tested with rainbow trout (Beckett et. al. 1976) ranged from < 1 mg/L to > 50,000 mg/L. In general, the organic polymers were extremely viscous and at high viscosities fish apparently were unable to circulate the material past the gills and mortality was due to suffocation. The inert soils such as clay tend to dissociate to some degree and it is possible that this chemical activity may be due to the addition of impurities from the manufacturing process. Observed acute affects with lignosulfonate compounds may be the result of acidic pH. The authors suggest that the acute toxicity of the

components fall under two categories, i.e., physical action such as high viscosity and suspended solids, and chemical action such as extreme pH and heavy metals.

Sprague and Logan (1979) observed in their studies that many of the organic materials (CMC, Ben-Ex, Kelzan-XC, SS-100, FLR-100 and Staflo) had relatively low toxicity and used in small quantities would not contribute to a serious environmental problem. However, paraformaldehyde, capryl alcohol and 5 of the 7 surfactants tested were fairly toxic with LC50 values < 100 mg/L.

In an additional aspect of their study, Sprague and Logan found no single pattern of joint action (calculated on the asumption that toxicities of individual components were additive). The additive action was approximately one half the results for single components. Less than additive toxicity was shown for 7 components in simulated drilling fluid and antagonism was demonstrated in 9 of 21 bioassays with single components added to simulated fluids.

In studies by Logan (1976, 1980) rainbow trout were tested in bioassays with ferrochrome lignosulfonate, torq-trim, sodium acid pyrophosphate, chromolet, Ben-Ex, Helzon-XC, caustic, capryl alcohol, Tri-Con, paraformaldehyde, Scot-Free, and B-Free. Five components: capryl alcohol, Tri-Con, paraformaldehyde, Scot-Free and B-Free had 96 hour LC50 values < 100 mg/L. The remaining chemicals had 96 hour LC50 values between 105-2270 mg/L.

Ageing of the various chemical components for 16 days eliminated or substantially reduced the toxicity of 5 of these 6 chemicals. The exception was B-Free where the median effective time (ET 50) was reduced to 4.6 hours from 930 hours.

In a more specific study, Hollingsworth and Lockhart (1975) studied the toxicity of thinning agents on sailfin molly (Mollienesia latipinna). Because of the importance and extensive use in the drilling industry lignosulfonates were tested along with phosphates, tannins, and lignites. Of the compounds tested the tannin class had considerably lower median tolerance limits than any of the other products. An example of a widely used tannin is quebracho. The suspected cause of the toxic response to this class is the oxygen scavenging characteristics of tannin. It is interesting to note that

chrome lignosulfonate and ferrochrome lignosulfonate were the least toxic in freshwater and marine experiments. Lignosulfonate compounds are the most widely used thinning agents today. For a more detailed discussion of the effects of selected components, see Land (1974).

IMPACTS: WHOLE DRILLING FLUIDS

Plants

Few studies have been published on the effects of whole drilling fluids on plant growth or changes in natural vegetation as a result of exposure to drilling fluids, although brief observations have been recorded at disposal sites or adjacent to drilling sumps (Smith and James 1980). Most information about the effects of drilling fluids on plants has been deduced from studies other than those using the fluids themselves. Bryant and Hrudey (1976) discussed the toxicity of drilling mud components based on chemistry derived from the literature.

Two master's theses from Utah State University, Honarvar (1975) and Pesaran (1977b), and a study by Miller and Pesaran (1980) provide the majority of useful information about the effect of drilling fluid mixtures on plants. The conclusions of the three investigations are similar indicating that fluids containing specific chemical components inhibit plant growth.

In general, the major inhibiting effect of drilling fluids which reduced plant growth is the result of excess soluble salt and exchangeable sodium. Large amounts of potassium chloride, in potassium chloride muds, is a good example and sodium salts (sodium-dichromate and sodium hydroxide) added in lesser amounts also reduced growth. Pesaran (1977b) also found that muds that contained diesel oil inhibited growth, however, he observed this effect to be temporary.

Six of the seven muds tested by Miller and Pesaran (1980) contained sodium hydroxide in appreciable amounts. The inhibitory effects of these muds was attributed to the destruction of soil aggregation by the excess sodium. The muds rendered the soils impermeable or slowly permeable which were poorly aerated when wet and hard and structureless when dry.

The effects of drilling muds depends on the soil type. Drilling muds will be least detrimental on acidic, leached soils high in organic matter and most detrimental on alkaline loam to claying soils (Pesaran 1977a). When drilling muds which have alkaline pH values are added to strongly acid soils, there may be a beneficial effect on plant growth because of increased soil pH (Miller and Pesaran 1980).

The impact of waste drilling fluids (sump fluids) on soils and vegetation was studied in field plots of natural plant assemblages (Yonkin and Johnson 1980). In this investigation, field studies were conducted using the three basic drilling fluids used in Alberta, Canada, ie., potassium chloride, dispersed water gel and flocculated water gel.

Sump fluids derived from potassium chloride water-polymer muds had the highest salt concentration (up to 33,000 ppm anions and cations) and were most potentially harmful to soils and vegetation. Additional laboratory studies with these fluids also showed a significant reduction in seed germination. Fluids from freshwater gel drilling muds contained considerably lower concentrations of salt (up to 2055 ppm anions and cations) and exhibited significantly lower effects. The authors suggest that plant damage was related to direct contact and uptake of fluid components. Salt content of the sump fluids was most damaging to plant growth followed by diesel fuel. These results agree with those of Pesaran (1977b) and Miller and Pesaran (1980) and provide the added dimension of being conducted in the field with natural assemblages of vegetation.

Aquatic Animals

Freshwater amphipods, insects and fish have been used to study the toxicological properties of whole drilling fluids. Qualitative investigations such as Granthum and Sloan (1975), Hardin (1976), Shaw (1975), and Zitko (1975) offer insight into general effects of drilling and sump fluids on aquatic species.

A number of studies have been conducted to define the lethal threshold beyond which the normal functions of an organism, as well as its survi-

val, are adversely affected. A range of responses has been observed from behavioral studies with individual species (Lawrence and Scherer 1974), community response to drilling fluid discharge in a body of water (Lawrence 1980), survival and emergence of chironomid (Didiuk 1975, Didiuk and Wright 1976) to lethality (Logan 1980, Moore et. al. 1976, Beak Consultants 1974, Weir et. al. 1976, Weir and Moore 1975, Logan 1973, and Falk and Lawrence 1973).

Sublethal responses of whitefish and rainbow trout to drilling fluids and the supernatant fraction showed that whitefish were attracted to suspensions with increasing concentration over the concentration range tested (1-1000 µl/l). Visual perceived turbidity was speculated as one causal element in attracting this species (Lawrence and Scherer 1974). Rainbow trout exposed to the same range of mud suspension exhibited somewhat of a different response. Up to concentrations of 100 µl/l the fish showed a neutral response, however, at concentrations of 1000 µl/l, the trout shifted to a preference response. Drilling fluid supernatant elicited a biphasic response in both species, i.e., an initial attraction followed by avoidance at higher concentrations.

It has been shown by Herbert and Merkens (1961) that irritation of gell epithelium by suspended solids may not lead to a lethal stage in fish within 4 days (96 hours). However, mortality can occur abruptly after a long latency. This raises the question: Will whitefish and rainbow trout maintain their preference for mud suspensions at concentrations between 1000 µl/l and "lethal levels" (LC50 whitefish - 25,000 µl/l, rainbow trout 75,000 µl/l) and in essence be living in a "death trap"?

In a field study of some effects of drilling wastes on a small subarctic lake, Lawrence (1980) found no mortality to whitefish or nine spine sticklebacks that could be attributed to the sump fluid disposal. In fact, the author suggested that the movement of fish in and out of the lake was unchanged even though he measured an increase in turbidity, conductivity, alkalinity, total hardness, total iron, aluminum, chloride and sulfate ions. Although Lawrence observed a decrease in benthic biomass throughout the study the response was not uniform. For example, chironomid larvae decreased in abundance within 25 m of the outfall while nematodes and oligochaetes increased in abundance.

The decrease in chironomid larvae in response to drilling fluids, observed by Lawrence (1980), is consistant with observations by Didiuk and Wright (1976). Their study focused on the effects of deposition of thin (1, 3 and 7 mm) layers of drilling wastes on the survival of larvae of the chironomid, Chironomus titans, using emergence of adults as an index of survival. The authors found an inverse relationship between the thickness of mud and the percent emergence, i.e., control 84%, 1 mm - 61%, 3 mm - 47% and 12 mm - 12%. These results suggest that the mud represents a physical barrier to burrow construction and perturbation of feeding mechanisms. In addition, the authors postulated that delays in growth may result from large amounts of energy used for food gathering that could have been used for growth.

Qualitative studies are usually non-specific and can be compared in general terms, however, lethality studies are quantitative in nature and are usually defined by LC50, LD50 or TLM values. Table 3 lists ranges of 96 hour LC50 values of whole drilling muds on rainbow trout. The six studies cited provide values that range from very toxic (0.29 % fluid by volume) to relatively non toxic (85 % by volume). The studies by Moore et. al. (1976) and Weir and Moore (1975) indicate a wide range, 0.29-85 % and 9-70 % (by volume), respectively. In both studies drilling fluid was collected at various depths during drilling operations. In both studies the toxicity was related to changes in fluid composition from addition of components, in response to drilling conditions at various depths, and downhole contamination. The acute toxicity of the drilling fluids tested was directly related to the type of mud system used. Weir and Moore (1975) found that the toxicity of the drilling fluids collected while drilling near the surface (3000 feet) to be very high with LC50 values approximately 10 % by volume. The authors speculate that the toxicity was due to high chloride, calcium and conductivity from the potassium chloride-gel-polymer mud being used. From 4000-9000 feet, the fluids (unweighted gel-polymer mud) were moderately toxic, 5-6 fold decrease below that for the 3000 feet mud. The third mud system (weighted gel-barite system) used from 10,000-13,000 feet exhibited an increase in acute toxicity, LC50 9-16 % by volume.

A similar relationship was observed by Beak Consultants (1974) with LC50 values varying with depth of fluid collection, 4000 feet - 9.8 %, 6000 feet - 5.0 %, 7000 feet - 26 % and 8000 feet - 25 %. Along with the relation-

TABLE 3. TOXICITY OF WHOLE DRILLING FLUIDS TO RAINBOW TROUT (*Salmo gairdneri*)

Study	96 Hour LC50 (% by volume)
Moore et. al. (1976)	85 - 0.29[a]
Weir et. al. (1976)	59 - 3.23
Weir and Moore (1975)	70 - 9[b]
Lawrence and Scherer (1974)	7.5 - 4.2[c]
Beak Consultants (1974)	25 - 5
Logan et. al. (1973)	5.3 - 83

[a] Wide range due to changes in components used during drilling specific formations.

[b] Toxicity dependent upon depth of hole when sample collected.

[c] Calculated using the factor $\mu l/l \times 10^{-4}$

ship of depth (fluid chemistry) and toxicity, the authors also concluded that the toxicity was due to mud components, drilled solids did not effect the toxicity as much as components added. They also suggest that the toxicity resulted from metallic ions the source of which was barite and lignosulfonate.

The drilling fluid studies conducted by Falk and Lawrence (1973) were used to acquire information on the nature and amounts of drilling fluid compounds used, the efficiency of waste containment facilities and the toxicity of drilling fluids. Test animals (on site - lake chub and rainbow trout, laboratory - 9-spine stickleback) were exposed to sump fluids, composite sump fluids and drilling fluids. Drilling fluids were found to be acutely toxic with 96 hour LC50 values of 0.83 to 12.0 % by volume for lake chubb and rainbow trout. Sump fluids were comparatively less toxic with one sump yielding 96 hour LC50 of 22.5 and 81 % (by volume) for composite and surface sump fluids, respectively.

Finally, Moore et. al. (1976) concluded that both fluid components used and the formation drilled contributed to the overall toxicity of the mud samples tested. A great amount of variability in toxicity was related to the individual areas drilled, company and rig practices and conditions encountered. Four major sources of toxicity were identified; metal chlorides (e.g., potassium chloride), solids (e.g., barite), viscosity and speciality products (e.g., bactericides, rust inhibitors, crosslinking agents, alcohol defoamers, etc.). The only pattern which emerged from the data collected was that the overall toxicity of each sample was a result of the components in use at that particular time and the formation being drilled.

It is recognized that additional data may be found in large comprehensive reports which contain bioasay investigations as a small part of an overall assessment. No attempt was made to collate this data into the present report since most of the experiments were focused on very specific needs and would not add significantly to this report. In addition, it is also recognized that many petroleum companies and drilling fluid manufacturing companies have toxicity data, however, most of this information is proprietory and not available to the open literature.

SUMMARY

Drilling fluids are used in rotary drilling offshore and in land based operations. The fluids serve in a multiplicity of functions from lubrication to aiding in well logging operations. because of this wide range of functions drilling fluids are required to perform under extreme conditions yet must be sufficiently stable to maintain fluid integrity. Over 600 drilling fluids components are presently available for use in adjusting fluid characteristics to meet the needs of each drilling operation.

Drilling fluids get old and requirements change during the drilling of a well, thus, spent fluids are usually disposed of in a reserve pit on-site or in a designated disposal area. Both offshore (freshwater) and land based drilling operations dispose of spent drilling wastes in on-land facilities.

The introduction of these spent drilling fluids into the environment is a result of drilling mishaps and migration of liquid wastes from disposal sites. The resulting concern for environmental perturbation prompted effects research on drilling fluids components, whole drilling fluids and sump wastes.

Drilling fluids move through the environment in stream runoff, percolation through soils and groundwater aquifers. Metal uptake from drilling fluids, by plants has been shown to have a direct relationship with the concentration of the metals in rooting medium. The movement of discharged material in a lake from offshore drilling operations suggests that dilution is rapid and exposure to potentially toxic concentrations of chemicals is probably limited to a relatively small area adjacent to rig.

In terrestrial studies drilling fluid components, whole fluids and sump wastes have been shown to decrease seed germination, reduce growth and yields. In whole fluid experiments, the toxic component in each of the plant studies was postulated to be the salt content of the fluids.

Investigations involving fluids and aquatic organisms show a variety of toxicities depending on the component tested. In general, however, testing with rainbow trout showed some consistancy between investigations with a range of LC50 values from < 1 to 75,000 mg/l. Whole drilling fluids also showed a wide range of variability (0.29 to 85 mg/l) which was attributed in some

studies to the changing fluid composition purposefully altered to meet fluid requirements at various depths during drilling.

Preference/avoidance behavior has been observed with several fish species under varying concentrations of whole drilling fluids and fluid supernatant. The results of these studies suggest a preference by the fish for high suspended solids.

Several authors, Beckett et. al. (1976) and Beak Consultants (1974) differ in their causual evaluation of toxic effects of fluids on rainbow trout. The former attributing effects to physical and chemical characteristics of experimental fluids, the later indicating little effect from suspended solids. The potential impact of suspended solids was speculated that these solids (turbidity) may represent a "death trap" since they attract some species but potentially may cause latent mortality from gill damage (Falk and Lawrence 1973).

In general, studies with drilling fluid components and whole drilling fluids show a consistancy in toxicity testing. All of the studies show that some drilling components and whole drilling fluids are toxic to plant or animal species.

CRITIQUE AND RECOMMENDATIONS

In general, the data generated on the effects of drilling fluids and fluid components represents a good base for assessments of potential environmental perturbation. However, comparisons between data bases is somewhat questionable since in some studies pre-alteration of the test material (e.g., adjusting the pH) took place while in others unaltered fluids and components were used. Several bioassay studies were performed where aeration or resuspension of the fluids was accomplished throughout the study. The effect of this on the results, when compared to strictly static experiments, is unknown.

A problem one faces in evaluating toxicity data is the lack in uniformity of specific testing protocols, the variety of test organisms used, and the dimensions used in expressing toxicity values. The latter presents difficult problems when comparing test results by independent researchers, even though the compounds used are the same. This problem is even more exaggerated in the testing of whole muds and mud mixtures.

Interpolation of whole fluids toxicity from individual component studies has also been shown to be highly questionable, thus, making whole drilling fluids the prefered method. Confusion between some toxicity results is a function of interpretation of the data and should be scrutinized closely and compared with the corresponding data.

A hazard assessment for drilling fluids must include both effects and exposure components. Most of the data collected thus far has been on effects; the exposure component has been sadly neglected in freshwater and terrestrial research. The role that preference/avoidance behavior has in toxicity testing must be determined before extrapolation of *in vitro* testing results can be made into the field with any confidence.

Additional *in situ* studies are needed to determine community response to drilling wastes. We have seemingly generated sufficient toxicological information to say that drilling fluids and sump wastes represent a toxic pollutant in the environment. Toxicity data indicates that the obvious follow-up would be to conduct *in situ* studies in freshwater and terrestrial

habitats to determine the overall effect of these materials on the habitat and endemic biota. These studies integrate exposure, toxicity, behavior, and endemic species under exact environmental conditions. It seems unwise to rely so heavily on so few field studies and a number of laboratory experiments with components, the toxicity of which may not be additive, for decision making.

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